

# Ultrafast Directional Beam Switching in Coupled VCSELs

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## Abstract

We propose a new approach to performing ultrafast directional beam switching using two coupled Vertical-Cavity Surface-Emitting Lasers (VCSELs). The proposed strategy is demonstrated for two VCSELs of 5.6 microns in diameter placed about 1 micron apart from the edges, showing a switching speed of 42 GHz with a maximum far-field angle span of about 10 degrees.

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The limit to switching and modulation speed of semiconductor lasers is the most fundamental bottleneck for information processing and transmission in optical communication systems. This limit comes from the relatively slow carrier recombination lifetime in the III-V semiconductors used for optical applications. Though progress in pushing this limit in the past has been remarkable, such incremental improvement cannot meet the insatiable demand for higher speed in the long run. New paradigm has to be explored to maintain the momentum of the technology development.

The ability to steer or switch propagation direction of a laser beam in a controllable way is very important for many applications, and especially for optical interconnect networks. Beam scanning and steering in edge emitting lasers have been realized using thermal control [1] and spatial phase controlling technique [2]. For optical interconnect application, all the well-known advantageous attributes of VCSELs make them especially appealing elements. However, the advantages of compact 2D VCSEL arrays cannot be fully taken of, if bulky external passive optical elements are used for routing and switching. For this reason, routers integrated together with VCSELs that can be controlled electronically are especially important to reduce the overall volume of interconnect network [3,4]. By creating a phase shift in part of a VCSEL, it was demonstrated [3,4] that up to 2GHz beam switching can be achieved with maximum swing angle of about 3 degree.

In this report, we propose a new strategy for ultrafast beam switching well beyond the speed limit achievable with the traditional approach. Our proposal, based on two closely located VCSELs, is demonstrated through a detailed numerical simulation. Strong coupling between the two VCSELs through carrier diffusion and through evanescent light produce ultrafast hopping of laser intensity between two VCSELs, resulting an ultrafast far-field switching between two directions Directional switch of the far field by ten degrees at 42 GHz frequency is demonstrated. This proposal has great potential for further improvement. Both the switching speed and angle can be engineered with relative ease by adjusting the coupling strength between VCSELs.

Our simulation begins with the effective Bloch equations(EBEs) [5], which are con-

constructed from the microscopic theory. This model has been used recently to simulate transverse mode dynamics in VCSELs [6,7]. The model consists of three coupled equations describing diffraction of laser field, carrier diffusion in the transverse plane, and optical gain and refractive index dynamics represented by an effective polarization  $P_1$ :

$$\frac{n_g}{c} \frac{\partial E}{\partial t} = \frac{i}{2K} \nabla_{\perp}^2 E - \kappa E + i \frac{\delta n(x, y) K}{n_b} E + \frac{i K \Gamma}{2 \epsilon_0 \epsilon_b} (P_0 + P_1), \quad (1)$$

$$\frac{\partial P_1}{\partial t} = [-\Gamma_1(N) + i[\delta_0 - \delta_1(N)]] P_1 - i \epsilon_0 \epsilon_b A_1(N) E \quad (2)$$

$$\begin{aligned} \frac{\partial N}{\partial t} = & \nabla_{\perp} D_N \nabla_{\perp} N - \gamma_n N + \frac{\eta J(x, y)}{e} + \\ & + i \frac{L \Gamma}{8 \hbar} [(P_0 + P_1)^* E - (P_0 + P_1) E^*] \end{aligned} \quad (3)$$

where  $P_0 = \epsilon_0 \epsilon_b \chi_0(N) E$ . The variables and parameters are defined as follows:  $E$  is the slowly time-varying complex amplitude of the laser field and  $N$  is the 2D carrier density.  $P_0$  and  $P_1$  are complex polarizations of the semiconductor medium induced by the laser field.  $n_g$  and  $n_b$  are group and phase refractive index of the unexcited semiconductor.  $c$  is the speed of light and  $\epsilon_0$  is the dielectric constant, all of the vacuum.  $K = 2\pi n_b / \lambda$  is the optical wave-vector in the medium, where  $\lambda$  is the wavelength.  $\gamma_n$  is the carrier decay rate.  $\kappa$  is the loss due to cavity transmission and background absorption. It is related to the corresponding decay rate  $\tilde{\kappa}$  through  $\kappa = \tilde{\kappa} n_g / c$ . The value of  $\tilde{\kappa}$  is taken as 0.52 per picosecond in this paper. The  $\nabla_{\perp}$  represents spatial derivatives with respect to  $x$  and  $y$ , which are transverse to the propagation direction.  $\delta_0$  is the detuning between the reference and bandgap frequencies. The diffusion constant is taken as  $D_N = 20 \text{ cm}^2/\text{s}$  and the carrier decay constant is assumed a value of one inverse nanosecond. The cavity length  $L$  is one half of the wavelength. The  $\delta n(x, y)$  in the third term in equation (1) defines the index confinement profile which can represent any engineered index confinements, such as those due to oxidations. The gain confinement is represented by the space-dependent current profile  $J(x, y)$ , which also defines locations of VCSELs. The rest of parameters and the construction of the model equations are given in detail elsewhere [5].

In our simulation, the EBE model given above is solved using finite-difference method in

space and time domains directly without assuming a priori any mode structure or number of modes. At a given pumping (DC-bias) level, the simulation is performed over a period of several nanoseconds. This simulation time is longer than any intrinsic time scales in the system to ensure that only the long term behavior of the lasers is kept. The simulation result is the space and time resolved complex field amplitude  $E(x, y, t)$ , from which near- and far- field intensities are obtained. As an example, the simulation is performed for gain-guided VCSELs of 5.6 microns in diameter separated 0.8 microns edge-to-edge apart. In all the examples shown below, both VCSELs are biased slightly above threshold of individual VCSELs. Only one of them is modulated with a sinusoidal signal with an AC amplitude 1 percent of the DC bias.

Fig.1 shows snapshots of near field (top row) and the corresponding far-field (bottom row) intensities at a modulation frequency of 42 GHz. We see that there are two peaks in both the near-field and far-field patterns, resulting from two lasers. As the coupling bring the near field back and forth between the two locations, the corresponding far-field switches between two directions separated by about 10 degrees.

In Fig.2(a) we show time evolution of the near-field. The dashed curve shows the total intensity out of the VCSEL at the right hand side, while the solid curve shows the total laser intensity of the both VCSELs. We see that even the total laser intensity shows an oscillation with negligible modulation depth, the intensity of the right-side laser shows very deep oscillation. The corresponding Fourier transforms of the two data sets are shown in the lower part of the figure (Fig.2b), where we see the power spectrum of the right-side laser (dashed curve) shows a very pronounced peak around 42 GHz. The corresponding peak for the total intensity of the both lasers shows a much lower peak. The peak around 3.5 GHz in either curve corresponds to the relaxation oscillation frequency of the individual lasers. The small modulation depth for the total intensity and a much larger depth for the individual laser intensity indicate that the two lasers are performing anti-phase oscillation. The spatial averaging leads to cancellation of the modulation depth for the total intensity of the two lasers. This is most clearly exhibited in Fig.3, where we plot the time evolution of local laser

intensities taken at centers of two VCSELs, as indicated by “left” and “right” in the figure. We see clearly that the peak intensities of the two VCSELs are anti-correlated, showing an oscillation at the modulation frequency of 42 GHz. In Fig.3(b), the far-field intensity at two angles separated by 6 degrees is plotted, showing again an anti-phase oscillation or beam switching between the two angles at 42 GHz. The maximum span of the switching angle is about 10 degrees. Another feature to be noted is that the far field intensity extremes appear when the near field intensities have equal value, showing a maximum constructive interference at an angle about the normal direction of the laser facet. The smaller trough value at positive 3 degree than at the negative 3 degree is due to a slight tilt of the laser beam to the positive direction. As demonstrated clearly in fig.3, the beam switching at 42GHz is related to the hopping of peak intensity between two lasers. This hopping is caused by the coupling between the two VCSELs. To confirm this understanding, we varied the inter-vcsel separation. When the separation decreases, the beam switching frequency increases, and vice versa. At 1 micron separation, the beam switching frequency is about 38 GHz. We also studied the influence of DC bias and found that the increase DC current can result an increase in modulation frequency. This is because the increased DC pumping increases the spatial carrier overlap between the VCSELs. That, in turn, increases the effective coupling. It is straightforward to conclude that, whenever the coupling strength increases, the beam switching frequency will increase. This obviously gives some design flexibility to engineer the beam switching frequency and angles. For example, if farther separation is desired, an anti-guiding type of coupling can be adopted to maintain the strength of coupling and thus the switching frequency. VCSEL arrays based on anti-guiding coupling have been recently demonstrated by several groups [8,9]. Directional beam switching using anti-guide-coupled VCSELs is currently under study and results will be reported elsewhere.

It is important to note the difference between the approach we described in this letter and the one demonstrated recently [3,4]. In that approach, beam switching is achieved by separately pumping the two halves of the same device that show destructive interference due to the presence of the phase-shifted area. As noted by those authors, that approach, while

achieving an impressive 2 GHz modulation frequency, is limited by the relaxation oscillation frequency and the carrier diffusion. This approach is subject to the typical speed bottleneck as in the case of standard laser modulation, which is typically around a few gigahertz. In our approach, the relaxation oscillation frequency is no longer a limiting factor. Instead, a new resonance is created by the coupling of the two lasers, which is over 40 GHz for the case reported in this paper. Physically, both lasers will operate in the fundamental Gaussian-like mode, when each laser is operated separately. However, when the coupling is introduced, the original fundamental mode is no longer a steady state solution of the coupled system. Instead, the coupled system is now oscillating between the two possible solutions. This leads to the oscillation and directional beam switching. Obviously the switching frequency is determined by the coupling strength, as in any such coupled system consisting of the two sub-systems (oscillators).

In Summary, we have proposed a new approach for ultrafast directional beam switching using coupled VCSELs. This approach is demonstrated to achieve over 40 GHz beam switching frequency. Furthermore, we point out that this approach is easy and flexible for design to achieve different switching frequencies and angles. This switching scheme is likely to be useful for ultrafast optical networks at frequencies much higher than achievable with other approaches. At the same time, the proposed scheme can be used for other applications where ultrafast direct modulation is desired beyond the typical limit imposed by the long carrier lifetime. Implimentation of this approach for anti-guide coupled VCSELs and other related applications will be explored in future publications.

## FIGURE CAPTIONS

Fig.1: Snapshots of the near- (top row) and far- (bottom row) field intensity at three different moments in time showing lobe hopping and beam switchings. Both lasers are DC-biased slightly above threshold, while one of the laser is AC-modulated at 42 GHz with an amplitude that is one percent of the DC bias. The same pumping conditions apply to all the remaining figures.

Fig.2(a): Time evolution of the total intensity of two lasers (solid line) and that of the right-hand-side laser (dashed line); Fig.2(b): The corresponding power spectrum for the two data sets with same line styles.

Fig.3(a): Time evolution of the local near field intensity at the centers of two lasers showing the anti-phase oscillations of the VCSELs; Fig.3(b): Time evolution of the far-field intensity at two angles symmetrical about the normal direction and separated by 6 degrees showing the beam switching.

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